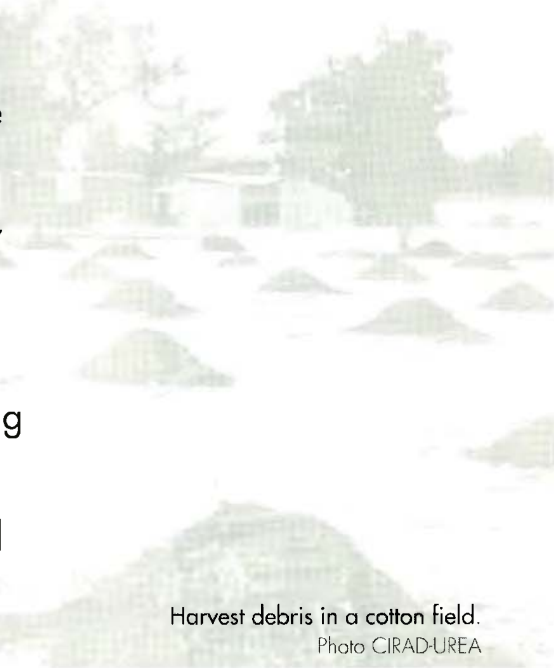
3. Integrated pest manag techniques and resource

Cotton growers generally rely on chemical treatments to control serious infestations by a wide range of pests, as immediate visible results can be obtained.
There are many risks associated with repeated pesticide treatments, e.g. upsetting the established insect fauna balance, development of pesticide resistance, possibility of intoxicating farmers, and environmental pollution.
For several years, CIRAD entomologists have been conducting studies in cotton fields with the aim of limiting pesticide use through development of an integrated approach to pest management involving various control techniques.



Harvest debris in a cotton field.
Photo CIRAD-UREA

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Cotton crops are threatened by a very wide range of pests, with a list of more than 70 arthropod pest species — mainly homopterans (jassids, aphids and whiteflies), heteropterans (bugs and mirids), lepidopterans (leaf- and boll-eating worms) and coleopterans, as well as mites (Tarsonemidae and Tetranychidae), diplopods and nematodes (Table 1). In tropical Africa, there can be losses of 30% to 100% of the crop yield potential due to infestations of these pests.

Chemical pest control is still essential in many agrosystems. Nevertheless, to reduce the dependence on pesticides for crop protection, adapted cropping techniques, plant varieties with insect-tolerant traits, entomophagous insects, entomopathogenic agents and chemical mediators should be taken into serious consideration.

This review mainly focuses on CIRAD projects under way in tropical Africa, as well as Latin America and Southeast Asia.

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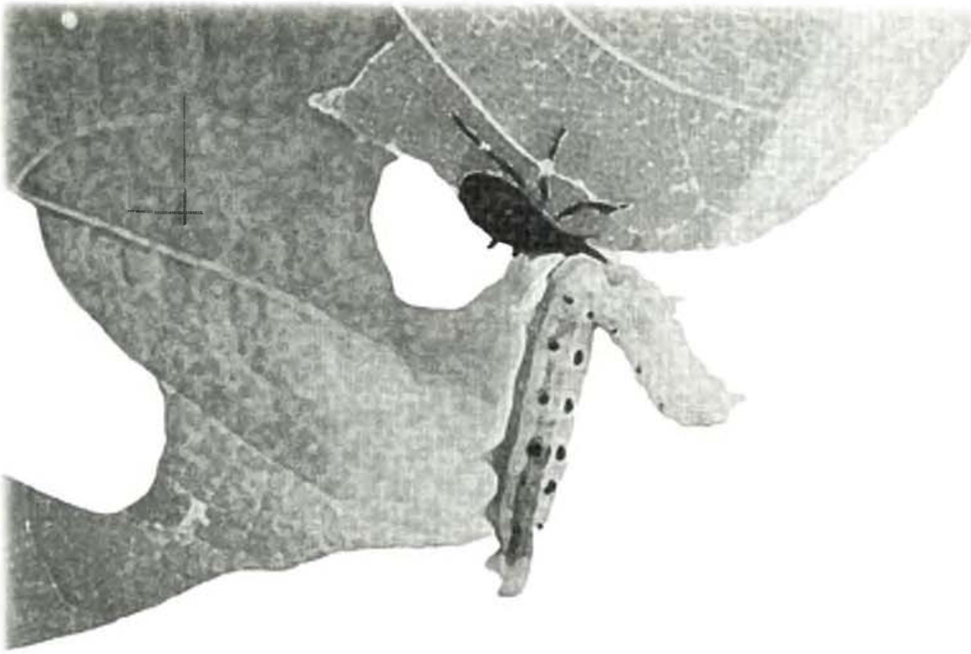


A larval *Asopinae* insect preying on a *Spodoptera littoralis* worm.
Photo CIRAD-UREA

Cultural practices

This involves all crop management practices: sowing, intercropping, planting density, weeding, monitoring plant growth and fertilization.

Plant and pest life cycles

Cotton growth and development cycles should be monitored in terms of the dynamics of the pest population present. In addition, the flowering period, factors prompting the fall of flowering and fruiting organs, and the plants' compensation potential should be generally understood when making treatment decisions.

In the African areas studied, plants sown early generally yielded the most cotton because of the favourable climatic conditions. However, another type of crop is planted at the beginning of the crop season, to avoid cotton pest attacks.

In central Côte d'Ivoire, before the advent of pyrethroids, farmers were thus advised to use the maize-cotton crop sequence to control *C. leucotreta* damage (ANGELINI, 1963).

Intercropping

In some countries, hardy cotton species (often *Gossypium arboreum* L.) are intercropped with other annual or perennial crops in traditional cotton cropping systems. This practice has continued with the introduction of *G. hirsutum* L., especially in Southeast Asia (CROZAT *et al.*, 1997). Although there have not been many investigations on the pest control impact, it seems that intercropping various crop species with cotton can alter the population dynamics of some pests (i.e. favouring insects, or attracting them away from cotton plants), or boost beneficial insect populations (NIBOUCHE, 1995; SOGNIGBE, 1989).

Weed control

DEGUINE (1995) began an inventory of refuges of beneficials for controlling *A. gossypii* populations in northern Cameroon. Although weeds can shelter pest populations in cropfields, they can also serve as a reservoir of beneficial entomophagous organisms which could, in some cases, be managed to the benefit of the cotton crop (PERRIN, 1975).

Fertilization

A few studies have highlighted that interactions between fertilization and crop protection techniques can be complementary, i.e. crop protection programmes adapted to the crop potential have to be set up to enhance the cost-effectiveness of fertilizer inputs (JOLY, 1980; CRETENET & VAISSAYRE, 1986; EKUKOLE, 1992).

Destruction of harvest debris

The traditional practice of destroying harvest debris can be very efficient when there is a well-defined interval between crop seasons. Pests adapt to the absence of their host plants by undergoing diapause or migrating to other hosts or sites. The reduced number of host plants during the dry season or the cold season reduces the survival potential for species that cannot easily migrate.

Populations of monophagous or oligophagous insects that survive by undergoing diapause, especially the pink bollworm *(P. gossypiella)*, can be reduced by carefully destroying

Table 1. Inventory of insects referred to in the present article.

Family	Genus and species
Coleoptera	*Anthonomus grandis* (Boheman)
	Cheilomenes sp.
	Exochomus sp.
Orthoptera	*Oecanthus* sp.
Homoptera	*Amrasca* spp.
	Amrasca biguttula (Ishida)
	Aphis gossypii (Glover)
	Bemisia tabaci (Gennadius)
	Jacobiasca spp.
Lepidoptera	*Alabama argillacea* (Hübner)
	Amsacta meloneyi (Druce)
	Anagasta kuehniella (Zeller)
	Anomis (Cosmophila) flava (Fabricius)
	Autographa californica (Speyer)
	Cryptophlebia leucotreta (Meyrick)
	Cryptophlebia peltastica (Meyrick)
	Diparopsis watersi (Rothschild)
	Diparopsis castanea (Hampson)
	Earias insulana (Boisduval)
	Earias biplaga (Walker)
	Helicoverpa armigera (Hübner)
	Helicoverpa zea (Boddie)
	Heliothis virescens (Fabricius)
	Mamestra brassicae L.
	Pectinophora gossypiella (Saunders)
	Spodoptera littoralis (Boisduval)
	Spodoptera exigua (Hübner)
	Spodoptera exempta (Walker)
	Spodoptera frugiperda (Smith)
	Spodoptera sunia (Guénée)
	Syllepte derogata (Fabricius)
Hymenoptera	*Aphelinus albidopus* (Hayat & Kausari)
	Brachymeria olethria (Waterson)
	Chelonus curvimaculatus (Cameron)
	Encarsia lutea (Masi)
	Eretmocerus mundus (Mundus)
	Gonozius sp.
	Microbracon kirpatricki (Wilkinson)
	Syrphophagus africanus (Gahan)
	Spodophagus lepidopterae (Delvare & Rasplus)
	Trichogramma brasiliensis
	Trichogramma lutea (Girault)
Heteroptera	*Rhinocoris albopilosus* (Signoret)
Mites	*Polyphagotarsonemus latus* (Banks)
Bacteria	*Bacillus thuringiensis*

harvest debris. This is done mechanically with a rotary cultivator or by feeding the green plant parts to livestock. Diapausing insects burrowed in the top soil layers can be efficiently destroyed by ploughing. Any chrysalides on the soil surface are generally destroyed by the heat or predators.

In Africa, cotton plants are also often cut up and burned. It is essential to destroy all stems and regrowth. Indeed, some pests (homopterans) can propagate on regrowth, which can also shelter infectious agents (viruses and phytoplasms). Ratooning, which is sometimes carried out by growers who have a shortage of seed, can enhance the possibility of pest propagation and infestations.

Pests can also be disseminated through seeds. It is important to strictly control seed being transported from one ecological zone to another — especially to avoid disseminating pink bollworms.

Varietal characters

A plant's resistance to pests can be of morphological, biochemical or genetically engineered (i.e. a variety modified by introducing foreign plant genes).

Morphological characters

Various morphological plant traits function as physical barriers to pests or alter their development conditions.

Variations in leaf hairiness

Leaf hairiness is the most commonly promoted morphological character. Hairy leaves hamper the development of jassids, i.e. African (*Jacobiasca* spp.) and Asian (*Amrasca* spp.) species. The efficiency of this trait depends on hair implantation patterns, length, shape and especially density (PARNELL *et al.*, 1949). Leaf hairiness is detrimental to insects' feeding and oviposition behaviours. This can stall pest infestations, which is a major advantage during the vegetative stage of the cotton plant. Cotton therefore does not have to be sprayed with pesticides, and beneficial insects (which are highly active during this period) will consequently not be endangered.

Conversely, it has been reported that glabrous leaves can hinder ovipositions of some lepidopterans, especially the *Heliothis virescens/ Heteroptera armigera* complex (BHAT *et al.*, 1986). This character is also useful for avoiding whitefly outbreaks (GERLING, 1990), but can favour aphid development (DEGUINE, 1995). According to WILSON (1986), under field cropping conditions, this glabrous trait helps avoid cotton fibre contamination by plant debris, whereas the entomological advantages are questionable.

Pectinophora gossypiella on a cotton flower.
Photo CIRAD-UREA

Lamina

The thickness, hardness and shape of the lamina — with "okra-type" laciniate leaves — could have a role in pest resistance. Some varieties with laciniate leaves are now being cropped on large cotton plantations, e.g. cv Siokra in Australia and cv Sudac K in Sudan. These "okra-type" leaves enable high air circulation, thus drying out pest larvae (e.g. *B. tabaci*) and enhancing pesticide penetration. DEGUINE (1995) focused on the impact of this character on *A. gossypii* outbreaks but found that it is not very efficient. Moreover, weed growth is favoured with this type of leaf cover as a considerable amount of light reaches the ground.

Bracts

Atrophied or absent bracts, or those that are separated from the cotton boll ("frego" bracts), can hinter ovipositioning by some lepidopterans and *A. grandis* infestations (ANGELINI *et al.*, 1965; JENKINS, 1989).

Nectary glands

As often pointed out, an absence of nectary glands can be beneficial, i.e. the cotton plant is not an interesting food source or attractive to certain insects (especially sucking pests). However, this character can be detrimental since beneficial insects are also affected.

Conclusion

In cotton, plant breeders have not promoted many morphological plant characters that are known to hamper pest attacks because they are often negatively correlated with technological aspects of the fiber (PAULY & VAISSAYRE, 1980).

Biochemical characters

Various biochemical pest-resistant characters of cotton plants — pH

Deltapine cultivar with "frego" bracts.
Photo CIRAD-UREA

Glossary

Antibiosis: the plant adversely affects the metabolism of the insect pest, sometimes to the extent of killing it.

Antixenosis: morphological or physiological characters of the plant that have a repellent effect on insect pests.

Attract and kill: a concept that involves attracting the insect with a sex pheromone and then killing it with a contact pesticide.

Chemical mediator: a volatile substance that provides the insect with certain information, thus altering its behaviour with respect to host plant choices, egg-laying sites and sexual partners.

Entomopathogenic organism: a microorganism (virus, bacterium, fungus) that can cause diseases in insect pests.

Hyperparasite: a parasite that can be parasitic to another parasite.

GV: granulosis virus, where a single virion is incorporated in a protein body.

Mating disruption: spraying a specific pheromone upsets male detection of females, thus reducing mating.

NPV: nuclear polyhedrosis virus, where several viruses are incorporated in an protein body.

Parasitoid: an organism that lives through part of its development cycle within the body of a host insect and subsequently causes its death.

Phytoplasm: microorganisms close to bacteria that are pathogenic to plants (previously called mycoplasmal organisms).

Pib: polyhedral inclusion bodies containing active viral elements or virions that are released in the digestive tract of the host insect.

Tolerance: the plant is able to withstand pest infestations, without being seriously damaged.

level of the cell contents, foliar turgescence, the plant's sugar, protein and mineral salt composition — modify pest behaviour and development. Chemical substances (gossypol, tannins, flavonoids) have an antibiotic effect on some pests such as *H. armigera*, jassids and flea beetles. In USA, many plant breeding studies are under way on these biochemical traits, but no significant results have been obtained to date (JENKINS, 1994).

In French-speaking Africa, there has been some success in breeding glandless cotton varieties, with the aim of promoting cottonseed and derivatives. More than 350 000 ha were cropped with glandless cotton in 1994-95. The problem is that the lack of gossypol glands weakens the plant's natural defenses, which means that pest management staff have to be highly vigilant. Glandless cotton plants can be attacked by many different insect pests at the onset of the growth cycle, especially coleopterans such as Halticinae species in Africa and Chrysomelidae species in Southeast Asia (BRADER, 1967; GENAY, 1994). Moreover, non-insect pests, which are rare in traditional cotton cropping systems, can be present with glandless varieties: birds during planting and rodents and other mammals during the harvest period.

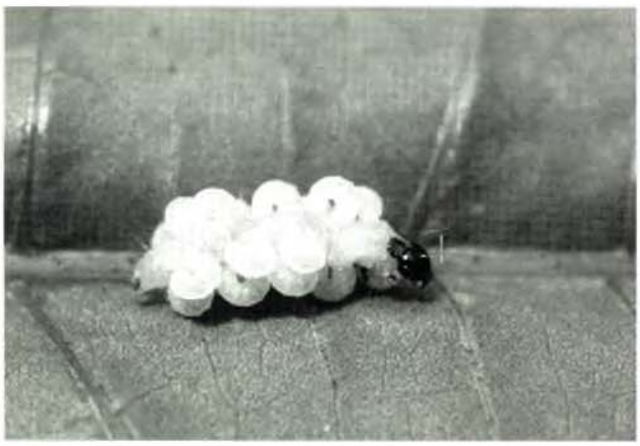
Transgenic cotton

Genes encoding toxins derived from the bacterium *Bacillus thuringiensis* can now be inserted in cotton plants through genetic engineering techniques. Genetically modified varieties are now available on the market (PANNETIER *et al.*, 1995).

Toxins corresponding to the genes *Cry IA(b)* and *Cry IA(c)* are active against the *H. virescens/H.armigera* complex and *P. gossypiella* (McINTOSH *et al.*, 1990). Recent tests by CIRAD highlighted that *Cry IB* has a similar spectrum of activity. *Cry IIIA*, a coleopteran-specific gene, could provide glandless cotton

Egg laying of *Trichogramma minutum* on *Helicoverpa armigera egg*.
Photo CIRAD-UREA

Spodophagus lepidopterae preying on a *Spodoptera littoralis* larva.
Photo CIRAD-UREA



Apanteles sagax larvae on *Syllepte derogata*.
Photo CIRAD-UREA

varieties with resistance to coleopterans in the Chrysomelidae family (SEKAR *et al.*, 1987).

Problems involved in introducing transgenic plants should not be overshadowed by the positive aspects of these innovations (e.g. improvement of common varieties). There is a considerable risk that some insects will quickly develop resistance to *B. thuringiensis* toxins (Mc GAUGHEY, 1985; TABASHNIK, 1994). Research programmes are primarily focused on insertion of genes coding for protease inhibitors, or other factors (e.g. oxidases), while attempting to minimize any possible development of resistance in the target pest. Secondly, precautionary measures that should be taken when cropping transgenic plants are being investigated in terms of mosaic cropping patterns, crop alternation, and refuge cropping with a mixture of transgenic and unmodified plants (GOULD, 1995).

Entomologists are also closely investigating how these genetic manipulations could upset the balance of the pest spectrum.

Entomophagous insects

Entomophagous insect populations evolve throughout the agrosystem, including cropfields, fallows and uncultivated host plants growing near farms.

There have been many studies aimed at identifying and enumerating auxiliary organisms in cotton cropping systems, while also investigating their roles in reducing pest populations and assessing unwanted side-effects of pesticides on these beneficial species. Indeed, very little is known about the wide variety of entomophagous insects.

Entomophagous insects have been inventoried in several African countries (Burkina, Cameroon, Côte

Cotton pest complexes

Cotton pest complexes have been reviewed by several research teams, including: SILVIE *et al.*, 1989; BOURNIER, 1991; DEGUINE, 1991; LECOEUR & VAISSAYRE, 1991; BAGAYOKO *et al.*, 1993; EKUKOLE, 1993; GALVA, 1993; SILVIE *et al.*, 1993; STREITO, 1994.

Auxiliary organisms observed on *H. armigera*

A long list of auxiliary organisms have been identified for *H. armigera* but, as is the case for most pests, this list is not yet exhaustive. *T. lutea,* an oophagous pest of the Trichogrammatidae family, was recently identified in Burkina.

Parasitoids of *S. littoralis*

No oophagous parasites have been reported for *S. littoralis.* In 1988, there was a major discovery of a new parasite, *S. lepidopterae* (Pteromalidae), with unusual biological characteristics, which have been the focus of some attention (BOURNIER & BENMOUSSA, 1993; RASPLUS & DELVARE, 1994). Possible hosts were identified by CIRAD research teams, i.e. *S. frugiperda, S. exigua, S. sunia* and *H. armigera.*

Parasitoids of *P. gossypiella* and *S. derogata*

In continental Africa and Madagascar, only a few parasitoid species have been reported on *P. gossypiella: Gonozius* sp. (Bethylidae); *Apanteles* sp. (Braconidae); *B. olethria (Chalcididae), M. kirkpatricki* (Braconidae), and *C. curvimaculatus* (Braconidae). A pest complex with a wide range of species was described for *S. derogata* in Chad and Togo (SILVIE, 1991 & 1993).

Parasitoids of *A. gossypii*

Many different insects feed on *A. gossypii.* Concerning predators, DUVERGER (pers. comm.) drew up a map of *Exochomus* spp. distributions in Africa. DEGUINE (1995) pointed out the high relative numbers of ladybirds (adults and larvae) and especially *Cheilomenes* spp. present in Cameroon. *A. albipodus* accounts for 56% of the overall parasitoid population in the same country, with *S. africanus* (Encyrtidae) and *Encarsia* sp. (Aphelinidae) representing 29% and 13%, respectively, of this population.

Auxiliary organisms preying on *B. tabaci*

Exochomus sp. was observed feeding on *B. tabaci* whitefly larvae in Mali (BAGAYOKO, 1989).
Green lacewing larvae prey on some whitefly larvae, but very few entomological field observations have been reported. A few parasitoids have now been identified, all belonging to the Aphelinidae family: *Encarsia* sp.; *E. lutea* (Mali, Cameroon); *E. transvena* (Benin, Burkina, Mali); *E. mundus* (Burkina, Cameroon, Mali).

d'Ivoire, Mali, Chad and Togo), and in Paraguay (MICHEL & PRUDENT, 1987). There are reference collections at CIRAD (Montpellier, France), in some countries (e.g. Togo), and at the International Institute of Tropical Agriculture (IITA) in Benin.

Data obtained on entomophagous insects in French-speaking Africa are summarized in Table 2.

Effects of some secondary host plants on their population dynamics

Secondary host plants for bugs and *A. gossypii* were identified along the edges of cottonfields (POUTOULI, 1994; DEGUINE, 1995), but very little is known about their roles with respect to beneficial insects.

As early as 1974, PEYRELONGUE & BOURNIER reported four parasitoids of larvae and one of *E. insulana* nymphs on a malvaceous plant (*A. asiaticum* L.) in Madagascar. In Burkina, parasitoids from *H. armigera* on tomato are mainly Tachninidae species, whereas hymenopterans are generally noted on cotton. Low parasitism levels occur on tomato and cotton, i.e. less than 5% (NIBOUCHE, 1994). In Togo, *Apanteles* spp. were observed on *Urena lobata* (Malvacae) leaves rolled by *S. derogata* caterpillars prior to planting the cotton crop. In Cameroon, parasitoids of *A. gossypii,* usually found on cotton plants, were detected with various bug species on cultivated plants (okra, sorghum) and

Table 2. Beneficial entomophagous insects identified in tropical Africa.

Country	Number of genera or species identified		Number of species identified		
	predators	parasitoids	hyperparasites	parasites oophagous	parasites of predators
Burkina	56	69	10	8	16
Cameroon	41	27	3	-	-
Mali	16	12	-	-	-
Chad	34	63	14	1	5
Togo	28	45	10	1	12

Larval ladybird (*Cheilomenes vicinia*) preying on aphids.
Photo J.-P. Deguine

wild plants (*Calotropis procera* Ait.R.Br.).

In the dry season, substantial infestations of parasites such as *A. albipodus* have also been noted on other host plants. It is therefore essential to take bug species other than those that damage cotton crops into consideration when assessing the population dynamics of beneficial species.

Prey that attract predatory bugs are also found on wild plants growing near cotton plants (SILVIE *et al.*, 1993; POUTOULI, 1994).

Role of auxiliary organisms under natural conditions

Auxiliary organisms were investigated in untreated fields.

Impact on some pest insect populations

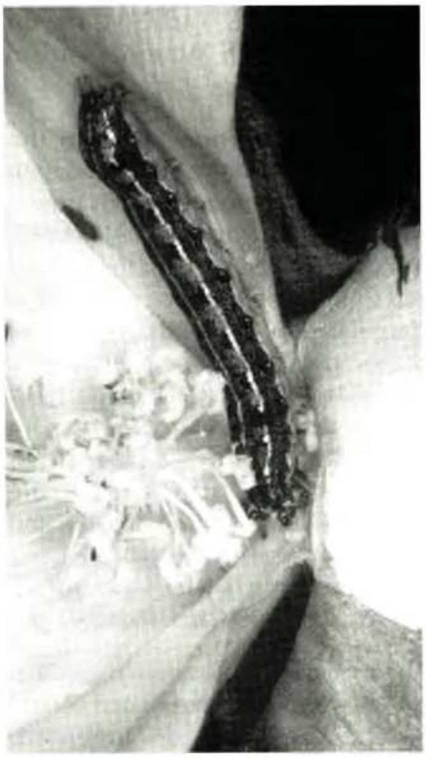
POUTOULI (1994) reported highly original data on oophagous parasitoids of bugs in Togo, where parasitism by various species ranged from 13% to 76%. In Burkina, samples of *H. armigera* populations were found to have a low rate of parasitism (1.4%), whereas pathogens induced high mortality (48.3%). In Chad and Togo, parasitism rates on *S. derogata* for various years ranged from 18% to 47% on worms and 21-23% on pupa, with high hyperparasitism (70%).

Studies were undertaken in the Central African Republic, Cameroon and Chad on entomophagous insects that prey on *A. gossypii* (VAISSAYRE, 1970; DEGUINE, 1995). On untreated fields, the predator complex is dominated by ladybirds (45-85% of the sampled population), followed by syrphids (14-37%) and green lacewings (up to 25%). Surveys in Togo and Benin revealed high local concentrations of some families such as Hemerobiidae and Chamaemyidae. These data are comparable to those obtained by MICHEL (1992 a & b, 1993) in Paraguay.

The dynamics of auxiliary organisms on *A. gossypii* in western and central Africa are well documented. Predators are active at the beginning of the crop cycle, then a fungal disease caused by *Neozygites fresenii* (Entomophthorales) appears from August on. Parasitoids occur at the end of the crop season (September, October), but their levels seem to be too low to have a serious impact on pest populations at this phase of the crop cycle.

The percentages of parasitism noted in Mali on *B. tabaci* showed that auxiliary organisms actually have a

Aphis gossypii first and second instars.
Photo J. P. Deguine.



Spodoptera littoralis on a cotton flower.
Photo CIRAD-UREA

considerable effect on crop pest populations: 9-23% for *E. lutea* and 6-25% for *E. mundus*.

The effects of predators have not yet been seriously quantified, as their activities are difficult to monitor under natural conditions. The effects of this type of auxiliary organism are also limited by parasitoids. Egg parasitism is hindered by specific behavioural activities, e.g. the male predatorial bug *R. albopilosus* (Reduviidae) guards its eggs until they hatch in order to ward off threatening parasitoids.

In addition, "opportunistic" predators (assassin bugs, spiders) sometimes attack other predators.

Entomophagous insects generally seem to have a moderate effect, except in terms of egg parasitism (a mechanism that has not yet been fully clarified). Hyperparasitic insects become active in the presence of high primary parasitoid populations (e.g. *S. derogata*).

All research conducted on the effects of auxiliary organisms and their practical interest should take these interactions into account.

Release of auxiliary organisms

In Madagascar, tests began as early as 1971 on introducing auxiliary organisms and rearing them for mass propagation and subsequent release in cotton cropfields (as part of a biological control programme). The aim was to delay the time of the initial pesticide treatment, as some cases of pesticide resistance had been reported (BOURNIER & PEYRELONGUE, 1973). The introduced parasite was a *T. brasiliensis* strain from El Salvador and *H. armigera* was the target pest. The imported strain was propagated on a substitute host (the pyralid *A. kuehniella*) before release. The results were not very encouraging as it was difficult to apply the technique in farmers' fields. Similar experiments were carried out more recently in Senegal (1979-1980), Togo and Cameroon (1982-1983) (SOGNIGBE, 1989; BOURNIER, 1991) using insects from CIRAD's Montpellier (France) laboratories.

Although considerable skills have been developed for studying auxiliary organisms, it is still difficult to apply the results on a large scale under tropical African cotton cropping conditions.

Table 3. Effects of various pesticide active ingredients on auxiliary organisms. (Source: SIGRIST *et al.*, 1994)

Active ingredient tested	Dose (g/ha)	Effects on ladybirds	Effects on syrphids	Effects on spiders
alphacypermethrin	18	highly toxic	highly toxic	non toxic
bifenthrin	30	highly toxic	highly toxic	highly toxic
cypermethrin	36	highly toxic	highly toxic	highly toxic
esfenvalerate	22	non toxic	non toxic	non toxic
fenvalerate	60	moderately toxic	non toxic	highly toxic
endosulfan	750	slightly toxic	highly toxic	highly toxic
chlorpyriphos-E	450	non toxic	highly toxic	highly toxic
chlorpyriphos-M	500	non toxic	highly toxic	highly toxic
dimethoate	400	slightly toxic	highly toxic	non toxic
isoxathion	350	slightly toxic	highly toxic	moderately toxic
isazophos	200	highly toxic	highly toxic	non toxic
omethoate	300	slightly toxic	highly toxic	moderately toxic
methamidophos	300	slightly toxic	slightly toxic	non toxic
monocrotophos	250	highly toxic	highly toxic	highly toxic
profenofos	150	highly toxic	moderately toxic	highly toxic
triazophos	125	slightly toxic	highly toxic	non toxic
benfuracarb	250	slightly toxic	slightly toxic	moderately toxic
carbosulfan	300	highly toxic	highly toxic	slightly toxic
thidicarbe	800	slightly toxic	slightly toxic	slightly toxic
imidacloprid	50	slightly toxic	slightly toxic	non toxic

Impact of active ingredients on auxiliary organisms

Since 1990, the effects of pesticide active ingredients have mainly been investigated in Chad, Cameroon and Côte d'Ivoire. Despite the methodological problems involved in these studies, an active ingredient classification has been drawn up on the basis of their results (Table 3).

Entomopathogenic agents

Insect populations are controlled by various epizootic diseases involving viruses, bacteria, fungi and protozoans. Research undertaken in Africa on this topic was first reviewed by ATGER (1970). Bibliographical summaries have been published on lepidopteran viruses and on using *B. thuringiensis* as a biopesticide. More recent results obtained in Cameroon and Togo have also been published (ANGELINI & JACQUEMARD, 1984; JACQUEMARD, 1987; MONTALDO, 1991; SILVIE *et al.*, 1993).

Insect viruses

When conditions are suitable for their development, epizootic viruses can have spectacularly destructive effects on some lepidopteran larval populations, e.g. *S. exempta* outbreaks in grass crops (Africa) and *A. argillacea* in cotton crops (Latin America).

Virus infections have been detected in most lepidopterans found on cotton crops in Africa, i.e. in major pests such as *H. armigera, D. watersi, E. insulana* and *C. leucotreta,* and in secondary species such as *S. exigua, Amsacta* sp. (ANGELINI & VANDAMME, 1969; CROIZIER *et al.*, 1983; ANGELINI & JACQUEMARD, 1984).

Virus infections were observed in *A. flava* in Mali and in *S. littoralis* in Chad (ATGER & CHEVALET, 1975; ATGER, 1970). However, no virus infections have been noted in the bollworm *P. gossypiella* or in the phyllophagous caterpillar *S. derogata.*

There have been several attempts to propagate locally isolated viruses (in Chad and Côte d'Ivoire), and finally experiments were conducted on using viruses isolated from other insects — at lower cost than would have been possible with locally produced viruses. The most commonly used pathogens are nuclear polyhedrosis viruses (NPV) from *A. californica* and *M. brassicae* (JACQUEMARD & DELATTRE, 1977; JACQUEMARD, 1978).

Some entomopathogenic viruses have been mass-reared *in vivo* from insect tissue cultures and marketed by pesticide manufacturers. CIRAD studies revealed that these products can be used to control some cotton pests (Table 4).

Table 4. Potential use of commercialized insect virus diseases (RIBA & SILVY, 1993).

Pathogen	Brand name	Origin	Potential target (species)
Heliothis NPV	Elcar	Switzerland	*H. armigera*
	Viron H	USA	*H. armigera*
	Biotrol VZH	USA	*H. armigera*
Spodoptera NPV	Spodopterin	France	*S. littoralis*
	Viron P	USA	*S. littoralis*
	Biotrol VPO	USA	*S. littoralis*
Mamestra NPV	Mamestrin	France	*H. armigera*
Autographa NPV	MGS 400	USA	*H. armigera*
Cydia GV	SAN 406	Switzerland	*C. leucotreta*
	Carpovirusin	France	*C. leucotreta*
	Granupom	Germany	*C. leucotreta*
	Decyde	USA	*C. leucotreta*

Research scientists have tried to utilize possible synergetic interactions between entomopathogenic agents and chemical pesticides — often pyrethroids at low doses (FERRON *et al.*, 1983). Studies on this feature were conducted in Cameroon, Côte d'Ivoire, Chad and Togo (JACQUEMARD, 1982; RENOU, 1987; MONTALDO, 1991; VAISSAYRE, 1994).

Treatment of cotton plants

Biopesticide treatments of cotton plants with these insect viruses are efficient when the control operator complies with a treatment schedule and a dose of 10^{13} Pib (polyhedral inclusion bodies) per hectare for most of the baculoviruses tested (CAUQUIL, 1985).

However, this efficacy is limited by:
– the biopesticide persistence, which is often insufficient because of the presence of antagonistic factors such as UV-rays or foliar secretions and their pH levels;

Virus-infected caterpillar on a cotton leaf.
Photo CIRAD-UREA

– the fact that the agent generally has to be ingested in order to become active, which is always difficult with bollworms (but phagostimulants can be added to enhance ingestion);
– the specificity, i.e. requiring propagation of the strains so as to control the constantly changing nature of the parasitism;
– the problems that arise in obtaining suitable quantities of the virus, which is propagated on reared insects or tissue cultures.

The most recent "combined control" strategy involved associating a polyhedral virus (usually NPV from *M. brassicae*), a phagostimulant and a low dose of chemical pesticide. The results in controlling certain bollworms (*H. armigera* and *D. watersi*) were as good as can be obtained with chemical pesticides (RENOU *et al.*, 1985; SILVIE *et al.*, 1993). Nevertheless, possible incompatible interactions (depending on the pesticide used) have to be taken into account. Combinations with pyrethroids generally give suitable results, whereas the use of some organophosphorus compounds (monocrotophos) can lead to a loss of efficacy.

In addition, the high cost of treatments, such as those recently tested in Cameroon and Togo, is a considerable constraint for the extension of microbiological techniques to control bollworms.

Entomopathogenic bacteria

In the entomopathogenic bacteria group, there are many opportunistic agents that can multiply to the extent of killing the host. Injuries generally provide a port of entry for these bacteria. However, only sporulating bacilli can infect healthy insects.

Infection mechanisms of identified bacteria

Most studies undertaken to date on entomopathogenic bacteria have focused on *B. thuringiensis* (ARONSON *et al.*, 1986; NBIAP, 1995). This gram+ bacterium forms crystals during sporulation, which contain toxins such as the ∂-endotoxin, i.e. the most important and only legally-applicable species. It is released after ingestion by the insect and binds to membrane receptors of the midgut, which is subsequently destroyed.

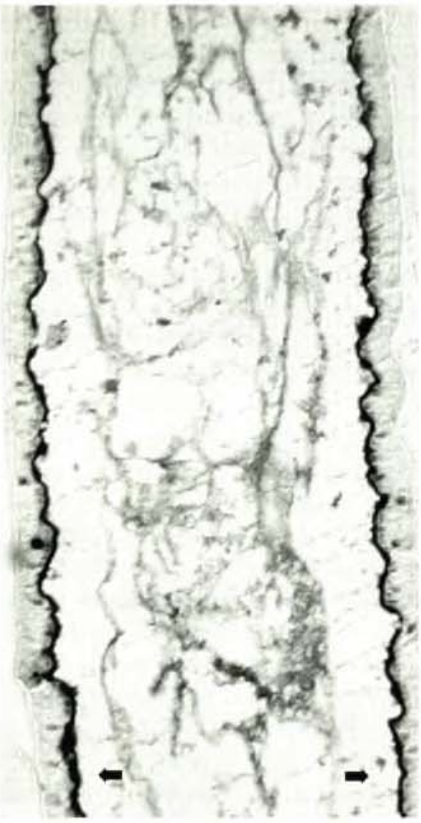
Initial investigations highlighted the activity of the Anduze strain against *E. insulana* (LE GALL, 1957; BURGERJON & GRISON, 1959). Other strains of this baccillus were then isolated from *D. watersi, E. insulana* and *A. moloneyi* (JACQUEMARD, 1965; ATGER & JACQUEMARD, 1965). Variations in the virulence of different strains of this bacterium against *Earias* sp. were noted in laboratory tests (FRUTOS *et al.*, 1987). All tested treatments conducted in cotton fields with *B. thuringiensis* formulations revealed the high efficacy of this bacterium against some pests, whereas it was found to be a poor biopesticide against bollworms (JACQUEMARD, 1987).

Other bacterial strains have been isolated *(Serratia, Pseudomonas, Aerobacter)* from diseased insects *(Diparopsis, Heliothis, Spodoptera),* but their biopesticide efficacy has not yet been tested. Hence, *B. thuringiensis* is the only bacterium that has been used as a biopesticide to control leaf-eating caterpillars, especially *S. derogata* and *A. flava.*

Prospects

Around 10 toxins from *B. thuringiensis* strains have currently been characterized. Genes that enable their synthesis have been identified, with their specificities determined in lepidopterans and coleopterans. A collection of toxins with high efficacy against cotton pest insects is available, and includes: *Cry IA(b), Cry IA(c), Cry IB* and *Cry IIA* genes for bollworms, *Cry IC* for *Spodoptera* sp. and *Cry III* for Chrysomelidae, pests of glandless cotton.

A cotton improvement programme has been set up to develop transgenic cotton plants expressing *B. thuringiensis* toxins. This marks an important turning point in the quest to control cotton bollworms that are relatively unsusceptible to standard



Map of receptor sites (located around intestinal microvilli) of the *Cry IAa* toxin (➡) in the midgut of *Chilo suppressalis*.
Photo L. Fiuza

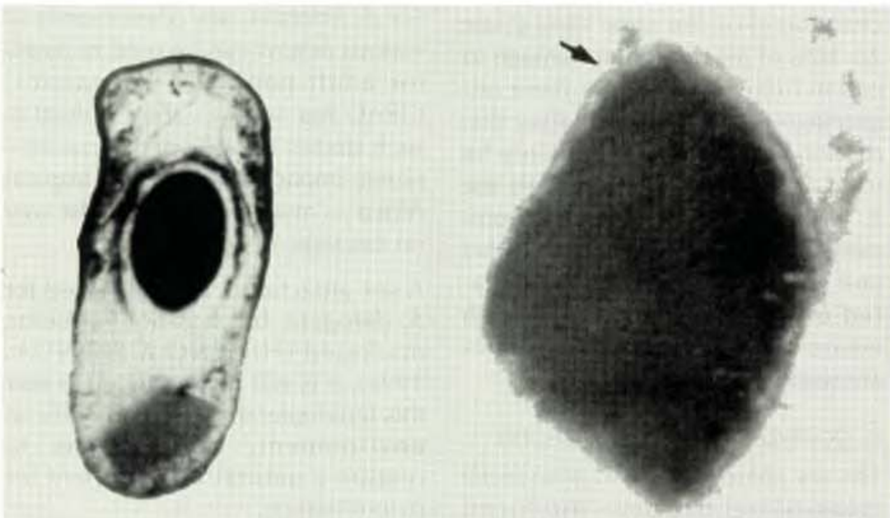
biopesticide treatments.

The role of entomopathogenic bacteria in integrated pest management programmes should therefore be reconsidered. *B. thuringiensis* formulations could be used as pesticides against phyllophagous caterpillars by determining the most suitable spraying techniques, possible associations with chemical pesticides and the best times, relative to the insects' development cycle, to conduct treatments (e.g. it is best to spray just-hatched neonate caterpillars) (DABI, 1988; HUSSEIN *et al.*, 1990; PLAPP, 1991). Transgenic varieties will have to be developed to control bollworms (BENEDICT *et al.*, 1992, 1993; GATEHOUSE *et al.*, 1992).

Entomopathogenic fungi

Epizootic diseases caused by Entomophthorales can be responsible for killing off insect populations under natural conditions. This phenomenon was noted for aphids in tropical Africa (SILVIE & DEGUINE, 1994). However, spray treatments with commercial mixtures, such as Mycar *(Hirsutella thompsonii)* or Vertalec *(Verticillium lecanii)* against *P. latus*, aphids and whiteflies, respectively, have failed. This was likely due to the fact that the most suitable ecological conditions for the action of these pathogens are still not clearly established.

B. thuringiensis spore and protein crystal.
Photo CIRAD-IGEPAM



Chemical mediators

For several years, sex attractants have been used to trap lepidopteran insects. CIRAD, in collaboration with the Chemical Mediator Laboratory of the French Institut national de la recherche agronomique (INRA), have developed a number of sex attractants such as pheromones from *H. armigera, C. leucotreta, E. insulana* and *D. watersi* (DESCOINS & GALLOIS, 1979; ANGELINI *et al.*, 1976, 1980, 1981). On the basis of this work, synthetic sex pheromones were used to investigate the population dynamics of adult males, e.g. *H. armigera, C. leucotreta, S. littoralis* and *P. gossypiella* (DAIBER, 1978; BOURDOUXHE, 1982). Unfortunately, the results of many tests carried out in seven different countries are not yet very useful for agricultural warning purposes or decision-making on pest control treatments (JACTEL & VAISSAYRE, 1988; MICHEL, 1992a and b).

In tropical African peasant farming conditions, mating disruption techniques are difficult to apply because of the fragmentation of cotton fields, staggered planting and fruiting dates, and technical treatment constraints.

Trapping and mating disruption

Studies conducted by CIRAD on this topic have focused on several different species.

H. armigera

The population dynamics of *H. armigera* were investigated, but very few or no correlations between captured males and crop damage in the field were noted. Eggs were observed before the adult males were captured, suggesting that the cotton fields are actually colonized by gravid females. The usefulness of trapping males to determine when pesticide treatments should be undertaken is therefore questionable.

Diparopsis watersi.
Photo J.-P. Deguine

Moreover, mating disruption would not be applicable for this polyphagous ubiquitous pest.

Tests on *D. watersi*

Very few tests have been carried out on *D. watersi,* apart from monitoring adult populations. It is possible to attract the first upsurging males of this monophagous pest to an early planted or pruned cotton trap-crop. A mating disruption or attract and kill trapping strategy could be used, combining a sex pheromone with glue or a pesticide.

E. insulana and *E. biplaga*

No studies have focused on *E. insulana* and *E. biplaga,* despite the fact that these two species (which are often found on the same sites) cause 20-30% of all caterpillar damage to cotton fruiting organs. For these oligophagous species, the mating disruption strategy would certainly be valid and readily possible. Only the *E. insulana* sex pheromone is commercially available. Moreover, this pest species can be quite easily reared on artificial medium, which means that more advanced studies are would be possible.

P. gossypiella sex pheromone

The sex pheromone of *P. gossypiella* (gossyplure) has been produced industrially for about 15 years. The results of many studies on diffusion of this pheromone have led to a wide variety of solutions (pheromone-soaked microfibres, tape or cord, and spraying water-suspensions of microgranules), that can be chosen to address different objectives, e.g. investigating population dynamics, mating disruption and, more recently, attract and kill (HENNEBERRY *et al.,* 1981; CRITCHLEY *et al.,* 1983; HOFER & BRAZZEL, 1992). Mating disruption is a popular control method, but the results have been quite variable (USA, Egypt, Pakistan). Interesting test results were obtained at Bouaké (Côte d'Ivoire): damage to fruiting organs was markedly reduced by manually spraying cotton leaves with glued microtubes (SANDOZ), at 5 000-8 000 microtubes/ha (VAISSAYRE, 1987) or using impregnated tapes (OCHOU, 1997). Persistence was higher than obtained with microgranulated formulations applied with standard spraying equipment.

C. leucotreta

There is a problem of specificity when conducting experiments on *C. leucotreta,* as males of other species are also captured in the traps, especially *C. peltastica.* There is no evidence that this lepidopteran could be controlled by mating disruption. This technique could be combined with that used to control *P. gossypiella* in areas jointly colonized by these two endocarpal bollworms.

S. littoralis and *S. derogata*

For *S. littoralis,* sex pheromones of various origins can be used to monitor adult population dynamics. CIRAD has not been too involved in such studies because of the low economic impact of this pest in tropical Africa — more research is under way on this topic in Egypt.

A sex attractant was synthesized for *S. derogata,* but it is not yet being marketed (HIMENO & HONDA, 1992). It is still quite difficult to rear this lepidopteran pest in an artificial environment, as it seems to require a natural environment for ovipositioning.

Beneficials

Phonoctonus, predator of *Dysdercus*.
Photo CIRAD-UREA

Coccinellidae eggs in an aphid colony.
Photo CIRAD-UREA

Coccinellidae larva feeding on an aphid colony.
Photo CIRAD-UREA

Spodoptera larva killed by *Bacillus thuringiensis*.
Photo CIRAD-UREA

Lacewing larvae feeding on whitefly pupea.
Photo CIRAD-UREA

Pentatonid bug infected by the *Beauveria* fungus.
Photo CIRAD-UREA

Future research on chemical mediators

Pheromones: availability and applications

Sex pheromones are not yet available for three species (*D. watersi, E. biplaga* and *S. derogata*), and there are no clear correlations between trapped insects and field infestations, especially with respect to *H. armigera*.

Mating disruption is only possible for oligophagous or monophagous insects *(P. gossypiella)*. Pests often colonize the same fields, i.e. both exocarpal species (e.g. *H. armigera, Earias* spp.) and endocarpal species (e.g. *P. gossypiella, C. leucotreta*).

Field applications

It would be very difficult to set up a network of traps around cropfields, even if organized by community associations (village communities). Simple inexpensive techniques requiring little labour input should be developed, especially for applying pheromones to induce mating disruption. The low number of emission sources and the persistence of the formulation should be future reseach focuses.

Regardless of the results of previous operations, the success of such projects will depend on how easily pheromones can be applied in traditional farming systems.

Conclusion

The intensity and complexity of most pest infestations certainly warrants the use of chemical pesticides. Treatments should, nevertheless, be conducted as part of an integrated pest management programme that also involves preventive measures, adapted cropping practices, rational choices of associated crops, and an overall understanding of the entomophagous insect complex (Table 5). Integrated pest management programmes for cotton cropping systems should also include destruction of harvest debris, tillage, intercropping, and well chosen planting dates and positions of the crop in the cropping plan.

It is essential to choose the most suitable cultivar to be cropped, i.e. physiological characteristics (length of its growth cycle, hardiness, compensation potential) and some morphological traits (especially leaf hairiness).

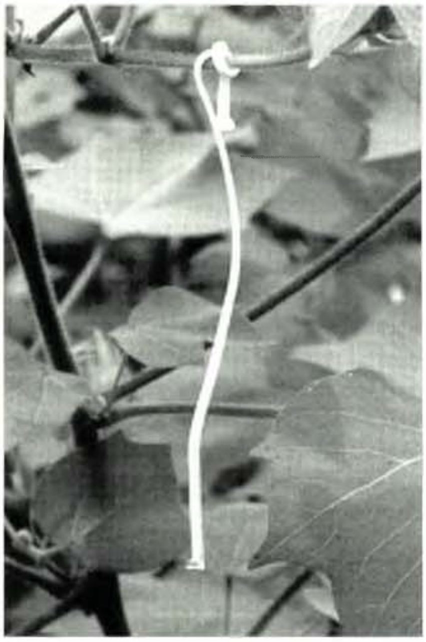
Integrated pest management programmes imply respect for the beneficial fauna. However, the results of mass releases of entomophagous auxiliary insects (e.g. trichogrammids for biological control) have generally

Table 5. Combined methods to control the main cotton pests as part of an integrated pest management strategy.

Pest	Cultural control	Varietal choices	Biological control (1)	Pheromones	Chemical control
H. armigera	* planting date	* transgenic varieties (*B. thuringiensis*)	** NPV:	* trapping	***
C. leucotreta	* planting date	* transgenic varieties	** NPV:	* trapping	***
P. gossypiella	*** destruction of harvest debris	* atrophied or frego bracts		*** mating disruption	**
Leaf-eating insects			** *B. thuringiensis*		***
Jassids		*** hairy leaves			
Aphids	* destruction of plants after harvest, topping, defoliant		** natural effect of beneficials and entomopathogens		** seed treatments
Whiteflies	* destruction of plants after harvest, topping defoliant	* "okra" leaves			**
Mirids		* nectariless varieties			
Bugs					***
Mites					***

*: established method; **: technique used on a reduced scale or with limited efficacy; ***: widely used technique of acknowledged efficacy.

(1): entomophagous insects and entomopathogens are included in the biological control category.



Sex pheromone-soaked cord attached to a cotton plant.
Photo P. Silvie

not been very encouraging. It is important to have an overall understanding of the population dynamics of the main entomophagous insects present in a region, so that they can be taken into consideration when making decisions on active ingredients to be used in pest control treatment programmes. Some entomopathogenic organisms efficiently reduce pest populations and treatments are therefore unnecessary (e.g. Entomophthorales against aphids). In some cases, microbiological preparations can be applied (e.g. viruses, *B. thuringiensis*) to control lepidopteran pests. Treatments against bollworms are more likely to be successful when conducted at carefully chosen times. Combining a pathogen with a low pesticide dose, i.e. a "combined control" strategy, will often enhance the efficacy of the pathogen.

Apart from gossyplure (used to disrupt *P. gossypiella* mating) and the aggregation pheromone of *A. grandis*, sex pheromones are not directly useful for pest control — however, they do provide informative results that could help in making treatment decisions. It should not be assumed that future transgenic cotton varieties expressing *B. thuringiensis* toxins will definitively solve all pest and disease problems with respect to this crop. Nevertheless, with the introduction of such new varieties, insect populations within cropping systems could be managed differently, unless they develop resistance to the toxins involved.

In conclusion, the results of these alternatives to chemical pest control are still not conclusive enough to be exploited. There are solutions for controlling some types of pests, for instance: leaf hairiness against jassids; entomophagous insects and entomopathogenic agents can reduce homopteran and lepidopteran pests; and some transgenic cotton varieties are efficient in controlling bollworms. However, substantial crop damage will still occur unless chemical pesticide treatments are used. To be economically sustainable in the short term, cotton crop management should be based on alternative cultural, varietal and biological methods, always combined with supervised chemical control. This is the current strategy adopted by CIRAD, through the development of new cotton pest management programmes in collaboration with its partners.

Damage to a young flower bud caused by *Earias biplaga*.
Photo J.-P. Bournier